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**FURTHER STUDIES OF LIQUID SLOSHING
IN ROCKET PROPELLANT TANKS**

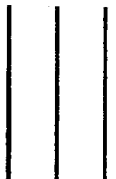
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H. Norman Abramson



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Contract NAS8-1555

SwRI Project 02-1072

Prepared for

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**National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama**

December 1965

**SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO HOUSTON**

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APPROVED:



H. Norman Abramson, Director
Department of Mechanical Sciences

ABSTRACT

This report presents a review of work accomplished under the present contract, covering the period 25 March 1961 through 31 December 1965, and is based upon summaries of the published papers and reports. Recommendations for future research are also given.

INTRODUCTION

The effects of liquid propellant slosh behavior on rocket vehicle design and development continue to be of great concern. In spite of major developments in propulsion capabilities, the demand for maximum payload and consequent weight saving in structural systems continues to stimulate design procedures for optimum baffle arrangements and effectiveness. Also, with increasing requirements for precise mission control and guidance has come the need for more detailed information regarding slosh forces in propellant tanks of varying geometry and for wide ranges of excitation conditions. The in-flight occurrence of several types of slosh-induced oscillatory motions has certainly given added impetus to investigations of liquid propellant dynamic behavior.

The research investigation conducted under the present contract is largely a direct continuation of work originally sponsored* by the U. S. Army Ordnance Missile Command of the Army Ballistic Missile Agency, and has been supplemented to some extent by another contract** with the NASA Office of Advanced Research and Technology. A brief discussion of related research programs at SwRI is given in the Appendix.

* Contract No. DA-23-072-ORD-1251

** Contract No. NASw-146

The general scope of work conducted under the present program may be described as: (a) investigation of slosh characteristics in cylindrical compartmented and spherical tanks, (b) evaluation of various aspects of baffle performance and effectiveness, and (c) an exploratory study of dome impact under launch abort or orbital docking conditions. The first of these areas of research, in addition to providing basic data on slosh forces under harmonic excitation, has pointed up the significant nonlinear effects occurring with these tank configurations. The effects of wall perforation in cylindrical tanks were also found to be unusual in several respects. Much new data of design import on ring baffle characteristics were obtained, particularly as regards perforation. It is planned that these research efforts will be continued under another contract.

The details of the several investigations conducted in each of the technical areas, and involving extensive laboratory studies and related theoretical analyses, are given in various Technical Reports published throughout the period of performance of this program. In fact, the present report is intended to constitute a review of work accomplished in this program by means of the summaries of papers and reports that have been issued, as listed in the following section.

SUMMARIES OF PUBLISHED PAPERS
AND TECHNICAL REPORTS

1. "Some Notes on Liquid Sloshing in Compartmented Cylindrical Tanks," by H. Norman Abramson, Luis R. Garza and Daniel D. Kana, Tech. Rept. No. 1, 15 February 1962 (also see, ARS Journal, 32, pp. 978-980, June 1962).

The present paper gives some results of experimental studies of frequencies and total force response in rigid cylindrical tanks compartmented into sectors by vertical walls and excited in translation. These data are correlated with theoretical values, where available. Some theoretical values for cylindrical tanks with annular cross sections are also shown for comparative purposes.

2. "Liquid Sloshing in Spherical Tanks," by H. Norman Abramson, Wen-Hwa Chu and Luis R. Garza, Tech. Rept. No. 2, 15 March 1962 (also see, AIAA Journal, 1, pp. 384-389, February 1963).

The purpose of the present paper is to present experimental data on the forced vibration characteristics of partially filled unbaffled and baffled spherical tanks. For the unbaffled tank, comparisons are made with previously measured natural frequencies and with the predictions of the Budiansky analysis. For the baffled tanks, comparisons are made with the force response predicted from an equivalent mechanical model.

3. "Liquid Sloshing in 45° Sector Compartmented Cylindrical Tanks," by H. Norman Abramson, Wen-Hwa Chu and Luis R. Garza, Tech. Rept. No. 3, 1 November 1962.

The present paper is a continuation of studies of liquid sloshing in compartmented cylindrical tanks. Experimental data on frequencies and total force response for a 45° sector compartmented tank are presented and correlated with theoretical frequencies and with similar data for 90° sector (quarter) tanks. This data shows the strong dependence of liquid natural frequency on excitation amplitude and a large decrease in natural frequency with increasing equivalent Reynolds number (based on perforation hole size). The experimental equipment and procedures are similar to those employed in previous work.

4. "Liquid Sloshing in a Spherical Tank Filled to an Arbitrary Depth," by Wen-Hwa Chu, Tech. Rept. No. 4, 15 December 1962 (also see, AIAA Journal, 2, 11, pp. 1972-1979, November 1964).

The kernel function for liquid sloshing in a spherical tank filled to an arbitrary depth is shown to be related to the Green's function of the second kind and is constructed successfully by numerical means. Natural frequencies are then computed as eigenvalues of a matrix. Eigen functions are obtained at a finite number of points as the eigenvectors which are sufficient for approximate evaluation of the force acting on the container. Simple formulas of force and moment are given for both pitching and translational oscillation under a fixed gravitational field. Finally, comparisons of predicted natural frequencies and force response with experiments for a quarter-full tank are also given.

5. "Measurements of Liquid Damping Provided by Ring Baffles in Cylindrical Tanks," by Luis R. Garza and H. Norman Abramson, Tech. Rept. No. 5, 1 April 1963 (also see, AIAA Journal of Spacecraft and Rockets, 1, 5, pp. 560-562, September-October 1964).

Measured data on the damping effectiveness of flat ring baffles in partially filled cylindrical tanks is presented in considerable detail. Particular emphasis is placed on the effects of baffle perforation.

6. "A Brief Comparison of Ring and Asymmetrical Baffle Characteristics," by Luis R. Garza, Tech. Rept. No. 6, 15 April 1963.

Because of the need to provide an adequate degree of damping of fuel sloshing in missile tanks, a constant search is being conducted for improved baffling systems. Upon completion of an extensive study of ring baffle damping and liquid resonance effects, it was decided to compare these results with experimental studies of equal area asymmetrical baffles. The experimental comparison is made for a number of directions of translation excitation and for various baffle depths below the liquid surface. The experimental procedure and test equipment are similar to those employed previously.

7. "A Preliminary Analysis for Optimum Design of Ring and Partition Antislosh Baffles," by Carl G. Langner, Tech. Rept. No. 7, 30 April 1963.

Presented here is a preliminary analysis of the factors involved in designing a minimum weight baffle system, composed of rings and/or partitions, to prevent excessive fuel sloshing in the propellant tanks of large rocket vehicles. By specifying over a given frequency range a maximum permissible force response due to liquid sloshing, a set of permitted combinations among the ring and partition baffle structures is determined, each of which sufficiently suppresses the liquid motion. The overall minimum weight baffle system is then determined from a strength analysis of the permitted baffle structures. Results of a typical example indicate that for moderate damping a plain ring baffle system has minimum weight.

8. "Measurements of Liquid Natural Frequencies and Damping in Compartmented Cylindrical Tanks," by Luis R. Garza, Tech. Rept. No. 8, 5 February 1964 (also see, AIAA Journal of Spacecraft and Rockets, 2, 3, pp. 453-455, May-June 1965).

This report presents experimental resonant frequencies and damping ratios for 45° , 60° , and 90° compartmented tanks. These are presented for various sector wall configurations and translational excitation amplitudes.

9. "An Exploratory Study of Simulation of Liquid Impact in Space Vehicle and Booster Tanks," by John F. Dalzell and Luis R. Garza, Tech. Rept. No. 9, September 1964.

This report summarizes exploratory work oriented toward the general problem of liquid impact in space vehicle and booster tanks. In part the work involved putting back in operation the impact test facility previously used in earlier work conducted for the ABMA. General fluid impact simulation studies were carried out with the conclusion that while fluid simulation for the launch abort case is possible in selected circumstances it is doubtful that simulation can be attained for every conceivable case. Similarly successful simulation of the general low gravity case in the laboratory is doubtful though apparently possible in particular instances. Since it does not appear possible to eliminate fluid scale effects in very many cases by experimental design, the magnitude of scale effect must be established. To this end a series of experiments to check for viscous and surface tension scale effects was planned and partially carried out on the fluid impact facility.

10. "A Comparison of Theoretical and Experimental Pressures and Forces Acting on a Ring Baffle Under Sloshing Conditions," by Luis R. Garza, Tech. Rept. No. 10, May 1965 (also, submitted for publication in AIAA Journal of Spacecraft and Rockets).

A comparison is presented of non-dimensionalized theoretical and experimental pressures and forces acting on a flat ring baffle under sloshing conditions. Comparisons are made for various baffle depths and for three values of tank excitation amplitudes. Force measurements for various perforated baffles are also presented.

11. "Moment of Inertia and Damping of Liquids in Baffled Cylindrical Tanks," by Franklin T. Dodge and Daniel D. Kana, Tech. Rept. No. 11, 4 June 1965 (also see, AIAA Journal of Spacecraft and Rockets, to appear).

The moment of inertia and the damping of a liquid in a completely filled, closed cylindrical tank is investigated experimentally for tanks with and without baffles. The results are compared with Bauer's mechanical model, and it is shown that a simpler model, which, however, is not conceptually correct for extremely large damping, is sufficient for cases where only small damping is expected. An approximate method of computing the liquid moment of inertia in a baffled tank is given.

RECOMMENDATIONS FOR FURTHER RESEARCH ON LATERAL LIQUID SLOSHING

The nonlinear aspects of lateral sloshing in cylindrical compartmented and spherical tanks noted in this research program demand further consideration. Even though the practical importance of these phenomena in applications of actual launch vehicles is as yet somewhat unclear, our analytical ability to explain and predict such nonlinear behavior is sufficiently limited that increased emphasis should be placed upon laboratory investigations. Efforts must also be directed toward the development of equivalent mechanical models of liquid sloshing that incorporate such nonlinear effects. Because these nonlinear aspects of the slosh forces and frequencies arise essentially as a consequence of tank geometry rather than of large amplitudes of excitation, careful attention should be given to data from future launch vehicle flight programs in an effort to detect the actual occurrence of any such phenomena.

The response of liquids in containers subjected to random excitation has virtually been ignored in previous investigations. An exploratory laboratory investigation would appear warranted.

Recently proposed advantages of so-called "flexible" baffles appear to be sufficiently attractive as to justify further investigation. The presently available laboratory data should be extended to encompass a broader range of baffle parameters and excitation conditions.

The ever-increasing importance of low gravity problems continues to demand additional study. Because of the very great difficulties in obtaining zero -g conditions in the laboratory, the full possibilities of simulation must be exploited and employed to complement drop tower and other similar programs.

ACKNOWLEDGEMENTS

The authors of the various papers and reports prepared under this program wish to express their appreciation to their many colleagues who provided so much valuable assistance during the course of the various studies. Particularly, thanks are due Mr. D. C. Scheidt for assistance in the experimental work, Messrs. V. Hernandez and D. DeArmond for preparation of drawings and report illustrations, and assistance in many other ways, and the entire staff of the SwRI Computer Laboratory. We also wish to acknowledge, gratefully, the guidance offered us by the various personnel of NASA-MSFC who served as Technical Monitors of this program: Dr. Helmut Bauer, Mr. Mario Rheinfurth, and Dr. George McDonough.

APPENDIX

RELATED RESEARCH PROGRAMS AT SwRI

The general research program covered in this report is to be continued under a new contract with NASA-MSFC, still in process of execution.

A program, initiated on 29 June 1963, is being carried out under Contract No. NAS8-11045, also with Marshall Space Flight Center. The area of research of this program generally concerns nonlinear effects in rigid and elastic tanks subject to longitudinal (vertical) excitation.

The Office of Advanced Research and Technology of NASA, under Contract No. NASr-94(07), is sponsoring the preparation of a comprehensive monograph on all aspects of liquid dynamic behavior in rocket propellant tanks. The monograph is now in process of final printing by NASA.

Two somewhat limited investigations are being conducted as part of the SwRI Internal Research Program, both dealing with nonlinear dynamics of partially-filled elastic shells.

Design problems associated with passive anti-roll stabilization tank systems for surface ships are similar in many respects to those of propellant sloshing in rocket tanks. Work in this area is being conducted under sponsorship of the U. S. Navy BuShips General Hydromechanics Research Program, administered by the David Taylor Model Basin under Contract No. Nonr-3926(00).

The various technical papers and reports prepared by SwRI under both completed and current contracts are listed in the following pages.

Technical Papers and Reports

on

LIQUID DYNAMICS IN ROCKET PROPELLANT TANKS

Published by

The Department of Mechanical Sciences
Southwest Research Institute
San Antonio, Texas 78206

1957-1965

I. U. S. ARMY ORDNANCE CORPS, ARMY BALLISTIC MISSILE AGENCY
(Contract DA-23-072-ORD-1062)

1. "Dynamic Loads Resulting From Fuel Motion in Missile Tanks" by Thomas B. Epperson and Robinson Brown, Final Report, June 1957.
2. "Dynamic Loads Resulting From Fuel Motion in Missile Tanks" by Thomas B. Epperson, Robinson Brown and H. Norman Abramson, Advances in Ballistic Missile and Space Technology, 2, pp. 313-327, Pergamon Press, New York, 1961.

II. U. S. ARMY ORDNANCE CORPS, ARMY BALLISTIC MISSILE AGENCY
(Contract DA-23-072-ORD-1251)

1. "Application of Similitude Theory to the Problem of Fuel Sloshing in Rigid Tanks" by H. Norman Abramson, Robert J. Martin and Guido E. Ransleben, Jr., Tech. Rept. No. 1, May 1958.
2. "Sloshing of Liquids in Cylindrical Tanks of Elliptic Cross-Section" by Wen-Hwa Chu, Tech. Rept. No. 2, September 1958 (also, ARS Journal, 30, pp. 360-363, April 1960).
3. "Simulation of Fuel Sloshing Characteristics in Missile Tanks by Use of Small Models" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 3, March 1959.
4. "Some Comparisons of Sloshing Behavior in Cylindrical Tanks with Flat and Conical Bottoms" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 4, May 1959 (also ARS Journal, 31, pp. 542-544, April 1961).
5. "A Note on Wall Pressure Distributions During Sloshing in Rigid Tanks" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 5, June 1959 (also, ARS Journal, 31, pp. 545-547, April 1961).
6. "A Note on the Effectiveness of Two Types of SLOSH Suppression Devices" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 6, June 1959.

7. "Simulation of Fuel Sloshing Characteristics in Missile Tanks by Use of Small Models" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 7, April 1960 (also, ARS Journal, 30, pp. 603-612, July 1960).
8. "Representation of Fuel Sloshing in Cylindrical Tanks by an Equivalent Mechanical Model" by H. Norman Abramson, Wen-Hwa Chu and Guido E. Ransleben, Jr., Tech. Rept. No. 8, June 1960 (also, ARS Journal, 31, pp. 1697-1705, December 1961).
9. "Free Surface Condition for Sloshing Resulting From Pitching and Some Corrections" by Wen-Hwa Chu, ARS Journal, 30, pp. 1093-1094, November 1960.
10. "Total Force Response Resulting From Liquid Sloshing in a Rigid Cylindrical Tank with a Vertical Center Wall Baffle" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 9, May 1961.
11. "Some Studies of a Floating Lid Type Device for Suppression of Liquid Sloshing in Rigid Cylindrical Tanks" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 10, May 1961.
12. "Liquid Sloshing in Rigid Cylindrical Tanks Undergoing Pitching Motion" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 11, May 1961.
13. "Theoretical and Experimental Studies of Liquid Sloshing in Rigid Cylindrical Tanks" by H. Norman Abramson, Final Report, May 1961.

III. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (Contract NASw-146)

1. "Discussion of Production of Rotation in a Confined Liquid Through Translational Motion of the Boundaries" by Guido E. Ransleben, Jr., and H. Norman Abramson, Journal of Applied Mechanics, 27, p. 365, June 1960.
2. "Some Studies of Liquid Rotation and Vortexing in Rocket Propellant Tanks" by H. Norman Abramson, Wen-Hwa Chu, Luis R. Garza and Guido E. Ransleben, Jr., Tech. Rept. No. 1, December 1960 (also, NASA Technical Note D-1212, January 1962).

3. "An Exploratory Study of the Effect of Sloshing on Heat Transfer in a Simulated Cryogenic Liquid" by H. Norman Abramson, Luis R. Garza and William Squire, Tech. Rept. No. 2, February 1961.
4. "A Discrepancy in the Published Results on Heat Transfer to Cryogenic Fluids" by William Squire, Int. Journal of Heat and Mass Transfer, 3, p. 347, (1961).
5. "Breathing Vibrations of a Circular Cylindrical Shell with an Internal Liquid" by Ulric S. Lindholm, Daniel D. Kana and H. Norman Abramson, Tech. Rept. No. 3, February 1962 (also, Journal of the Aerospace Sciences, 29, pp. 1052-1059, September 1962).
6. "Bending Vibrations of a Circular Cylindrical Shell Containing an Internal Liquid with a Free Surface" by Ulric S. Lindholm, Wen-Hwa Chu, Daniel D. Kana and H. Norman Abramson, Tech. Rept. No. 4, March 1962 (also, AIAA Journal, 1, 9, pp. 2092-2099, September 1963).
7. "An Experimental Study of Liquid Instability in a Vibrating Elastic Tank" by Daniel D. Kana, Ulric S. Lindholm and H. Norman Abramson, Tech. Rept. No. 5, January 1963 (also, AIAA Symposium on Structural Dynamics and Aeroelasticity, pp. 162-168, Boston, August 1965).
8. "Longitudinal Forced Vibration of Partially Filled Tanks" by Daniel D. Kana, Tech. Rept. No. 6, February 1963.
9. "Breathing Vibrations of a Partially Filled Cylindrical Tank—Linear Theory" by Wen-Hwa Chu, Journal of Applied Mechanics, 30, 4, pp. 532-536, December 1963.
10. "Studies of Liquid Dynamics in Rocket Propellant Tanks" by H. Norman Abramson, Final Report, May 1963.

IV. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION MARSHALL SPACE FLIGHT CENTER (Contract NAS8-1555)

1. "Some Notes on Liquid Sloshing in Compartmented Cylindrical Tanks" by H. Norman Abramson, Luis R. Garza and Daniel D. Kana, Tech. Rept. No. 1, February 1962 (also, ARS Journal, 32, pp. 978-980, June 1962).

2. "Liquid Sloshing in Spherical Tanks" by H. Norman Abramson, Wen-Hwa Chu and Luis R. Garza, Tech. Rept. No. 2, March 1962 (also, AIAA Journal, 1, pp. 384-389, February 1963).
3. "Liquid Sloshing in 45° Sector Compartmented Cylindrical Tanks" by H. Norman Abramson, Wen-Hwa Chu and Luis R. Garza, Tech. Rept. No. 3, November 1962.
4. "Liquid Sloshing in a Spherical Tank Filled to an Arbitrary Depth" by Wen-Hwa Chu, Tech. Rept. No. 4, December 1962 (also, AIAA Journal, 2, 11, pp. 1972-1979, November 1964).
5. "Measurements of Liquid Damping Provided by Ring Baffles in Cylindrical Tanks" by Luis R. Garza and H. Norman Abramson, Tech. Rept. No. 5, April 1963.
6. "Some Measurements of the Flutter of Ring Baffles in Cylindrical Tanks" by H. Norman Abramson and Luis R. Garza, AIAA Journal of Spacecraft and Rockets, 1, 5, pp. 560-562, September-October 1964.
7. "A Brief Comparison of Ring and Asymmetrical Baffle Characteristics" by Luis R. Garza, Tech. Rept. No. 6, April 1963.
8. "A Preliminary Analysis for Optimum Design of Ring and Vertical Wall Antislosh Baffles" by Carl G. Langner, Tech. Rept. No. 7, April 1963.
9. "Measurements of Liquid Natural Frequencies and Damping in Compartmented Cylindrical Tanks" by Luis R. Garza, Tech. Rept. No. 8, February 1964.
10. "Some Measurements of Liquid Frequencies and Damping in Compartmented Cylindrical Tanks" by H. Norman Abramson and Luis R. Garza, AIAA Journal of Spacecraft and Rockets, 2, 3, pp. 453-455, May-June 1965.
11. "An Exploratory Study of Simulation of Liquid Impact in Space Vehicle and Booster Tanks" by John F. Dalzell and Luis R. Garza, Tech. Rept. No. 9, September 1964.
12. "A Comparison of Theoretical and Experimental Pressures and Forces Acting on a Ring Baffle Under Sloshing Conditions" by Luis R. Garza, Tech. Rept. No. 10, May 1965.

13. "Moment of Inertia and Damping of Liquids in Baffled Cylindrical Tanks" by Franklin T. Dodge and Daniel D. Kana, Tech. Rept. No. 11, June 1965 (also, AIAA Journal of Spacecraft and Rockets, to appear).
14. "Further Studies of Liquid Sloshing in Rocket Propellant Tanks" by H. Norman Abramson, Final Report, December 1965.

V. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER (Contract NAS8-5468)

"An Analysis of the Quasi-Steady Liquid-Gas Interface in an Axisymmetric Tank During Low Gravity Transfer" by Wen-Hwa Chu, Final Report, February 1964.

VI. MARTIN-MARIETTA CORPORATION
DENVER DIVISION (Contract RZ 3-612053)

"Experiments on Liquid Dynamics in Titan II Propellant Tanks" by Daniel D. Kana, Final Report, February 1964.

VII. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
(Contract NASr-94(03))

"Some Studies of Nonlinear Lateral Sloshing in Rigid Containers" by H. Norman Abramson, Wen-Hwa Chu and Daniel D. Kana, Final Report, December 1964 (also, Journal of Applied Mechanics, to appear).

VIII. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
(Contract NASr-94(07))

"The Dynamic Behavior of Liquids in Moving Containers", edited by H. Norman Abramson, in press.

IX. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER (Contract NAS8-11045)

1. "A Review of Research Studies on Bubble Motion in Liquid Contained in Vertically Vibrating Tanks" by Franklin T. Dodge, Tech. Rept. No. 1, December 1963.

2. "Liquid Surface Oscillations in Longitudinally Excited Rigid Cylindrical Containers" by Franklin T. Dodge, Daniel D. Kana and H. Norman Abramson, Tech. Rept. No. 2, April 1964 (also, AIAA Journal, 3, 4, pp. 685-695, April 1965).
3. "A Resistive Wheatstone Bridge Liquid Wave Height Transducer" by Daniel D. Kana, Tech. Rept. No. 3, May 1964.
4. "Bubble Behavior in Liquids Contained in Vertically Vibrated Tanks" by Daniel D. Kana and Franklin T. Dodge, Tech. Rept. No. 4, August 1964.
5. "Subharmonic Oscillations in Arbitrary Axisymmetric Tank Resulting From Axial Excitation" by Wen-Hwa Chu, Tech. Rept. No. 5, September 1965.
6. "An Experimental Study of Liquid Surface Oscillations in Longitudinally Excited Compartmented Cylindrical and Spherical Tanks" by Daniel D. Kana, Tech. Rept. No. 6, September 1965.

X. GENERAL

1. "Amazing Motions of Liquid Propellants" by H. Norman Abramson, Astronautics, 6, pp. 35-57, March 1961.
2. "Liquid Dynamic Behavior in Rocket Propellant Tanks" by H. Norman Abramson, ONR/AIA Symposium on Structural Dynamics of High Speed Flight, pp. 287-318, Los Angeles, April 1961.
3. "The Falling Pendulum" by William Squire, ARS Journal, 32, pp. 263-264, February 1962.
4. "Some Recent Developments Concerned With Liquid Dynamic Behavior in Moving Containers" by H. Norman Abramson, invited lecture, ASME Applied Mechanics Division Annual Conference, Cornell University, June 1963 (also, Applied Mechanics Reviews, 16, 7, pp. 501-506, July 1963).

5. "Supplement to Breathing Vibrations of a Partially Filled Cylindrical Tank—Linear Theory" by Wen-Hwa Chu and Robert Gonzales, Journal of Applied Mechanics, 31, 4, pp. 722-723, December 1964.
6. "A Theory for Nonlinear Transverse Vibrations of a Partially Filled Elastic Tank" by Wen-Hwa Chu and Daniel D. Kana, Technical Report, Southwest Research Institute, November 1965.